

Claims

What is claimed is:

- [c1] A method for measuring neutron interaction properties of an earth formation, comprising:
 - irradiating the formation with bursts of high energy neutrons, the bursts having a duration selected to enable detection of short duration neutron burst related phenomena;
 - detecting, during or after at least one of the bursts, the short duration neutron burst related phenomena; and
 - after a selected number of the bursts, detecting long duration neutron burst-related phenomena.
- [c2] The method as defined in claim 1 wherein the long duration neutron burst phenomena comprise capture gamma rays.
- [c3] The method as defined in claim 1 wherein the long duration neutron burst phenomena comprise thermal neutrons.
- [c4] The method as defined in claim 1 wherein a length of time for the detecting long duration neutron burst related phenomena is selected to optimize a duty cycle for a pulsed neutron source used to perform the irradiating.
- [c5] The method as defined in claim 1 wherein a length of time for the detecting long duration neutron burst related phenomena and a number of the neutron bursts in a measurement cycle are selected to optimize a duty cycle for a pulsed neutron source used to perform the irradiating.
- [c6] The method as defined in claim 1 wherein a length of time for the detecting long duration neutron burst related phenomena is selected to optimize a statistical

precision of a measurement of a neutron capture cross section of the formation while optimizing a duty cycle for a pulsed neutron source used to perform the irradiating.

- [c7] The method as defined in claim 1 wherein a length of time for the detecting long duration neutron burst related phenomena and a number of the neutron bursts in a measurement cycle are selected to optimize a statistical precision of a measurement of a neutron capture cross section of the formation while optimizing a duty cycle for a pulsed neutron source used to perform the irradiating.
- [c8] The method as defined in claim 1 wherein a length of time for the detecting long duration neutron burst related phenomena is selected to optimize an accuracy of a long duration burst related measurement of a property of the formation.
- [c9] The method as defined in claim 1 wherein the short duration burst related phenomena comprise at least one of inelastic gamma ray related phenomena, neutron slowing down time related phenomena and short capture cross section related phenomena.
- [c10] The method as defined in claim 1 further comprising monitoring an output of a neutron source used to performed the irradiating, and normalizing measurements of short duration neutron burst related phenomena and neutron capture cross section made during the detecting thereof.
- [c11] The method as defined in claim 1 further comprising repeating the irradiating, the detecting short duration neutron burst related phenomena and the detecting long duration neutron burst related phenomena for a selected number of times, and detecting background radiation from the formation for a selected time interval thereafter.

[c12] The method as defined in claim 1 further comprising measuring the short duration neutron burst related phenomena after a plurality of the neutron bursts to improve a statistical precision of measurements made therefrom.

[c13] A method for measuring neutron interaction properties of an earth formation, comprising:
irradiating the formation with bursts of high energy neutrons, the bursts having a duration selected to enable detection of inelastic gamma ray related phenomena;
detecting, during each of the bursts, the inelastic gamma ray related phenomena;
and
detecting long duration neutron burst-related phenomena after a selected number of repetitions of the irradiating and the detecting inelastic gamma ray related phenomena.

[c14] The method as defined in claim 13 further comprising measuring neutron slowing down related phenomena after each of the bursts.

[c15] The method as defined in claim 13 further comprising repeating the irradiating, the detecting inelastic gamma ray related phenomena and the detecting long duration neutron burst related phenomena for a selected number of times, and detecting background radiation from the formation for a selected time interval thereafter.

[c16] The method as defined in claim 15 wherein a length of time for the detecting long duration neutron burst related phenomena and a number of the neutron bursts in a measurement cycle are selected to optimize a statistical precision of a measurement of a neutron capture cross section of the formation and a statistical precision of a measurement of the inelastic gamma rays while optimizing a duty cycle for a pulsed neutron source used to perform the irradiating.

[c17] The method as defined in claim 13 wherein a length of time for the detecting long duration neutron burst related phenomena is selected to optimize an accuracy of a measurement of neutron capture cross section of the formation.

[c18] The method as defined in claim 13 further comprising measuring short duration capture cross section related phenomena after each of the bursts.

[c19] The method as defined in claim 13 wherein the long duration neutron burst related phenomena comprise capture gamma rays.

[c20] The method as defined in claim 13 wherein the long duration neutron burst related phenomena comprise thermal neutrons.

[c21] The method as defined in claim 13 wherein a length of time for the detecting long duration neutron burst phenomena is selected to optimize a duty cycle for a pulsed neutron source used to perform the irradiating.

[c22] The method as defined in claim 13 wherein a length of time for the detecting long duration neutron burst phenomena is selected to optimize a statistical precision of a measurement of neutron capture cross section of the formation while optimizing a duty cycle for a pulsed neutron source used to perform the irradiating.

[c23] A method for logging earth formations, comprising:
lowering a pulsed neutron logging instrument into a wellbore drilled through the earth formations, the instrument comprising a controllable source of high energy neutrons and detectors adapted to detect neutron slowing down time related phenomena, neutron capture cross-section related phenomena, and inelastic gamma ray phenomena;
irradiating the earth formations with bursts of high energy neutrons, the bursts having a duration selected to enable detection of the inelastic gamma ray phenomena;

detecting the inelastic gamma ray phenomena during each of the bursts;
detecting the neutron slowing down time related phenomena after each of the
bursts; and
after a selected number of the bursts, detecting the long duration neutron burst-
related phenomena.

- [c24] The method as defined in claim 23 wherein the long duration neutron burst phenomena comprise capture gamma rays.
- [c25] The method as defined in claim 23 wherein the long duration neutron burst related phenomena comprise thermal neutrons.
- [c26] The method as defined in claims 23 further comprising detecting short duration capture cross section related phenomena after each of the bursts.
- [c27] The method as defined in claim 23 wherein the lowering into the wellbore comprises attaching the well logging instrument to a drill string and performing the irradiating, the detecting during at least one burst, the detecting after at least one burst, and the detecting after a selected number of bursts during drilling of the wellbore.
- [c28] The method as defined in claim 23 wherein the lowering into the wellbore comprises attaching the well logging instrument to one end of an electrical cable, and extending and retracting the electrical cable.
- [c29] The method as defined in claim 23 wherein a length of time for the detecting long duration neutron burst phenomena is selected to optimize a duty cycle for a pulsed neutron source used to perform the irradiating.
- [c30] The method as defined in claim 23 wherein a length of time for the detecting long duration neutron burst phenomena is selected to optimize a statistical precision of

a measurement of neutron capture cross section of the formation while optimizing a duty cycle for a pulsed neutron source used to perform the irradiating.

- [c31] The method as defined in claim 30 wherein a length of time for the detecting long duration neutron burst related phenomena and a number of the neutron bursts in a measurement cycle are selected to optimize a statistical precision of a measurement of a neutron capture cross section of the earth formations and a statistical precision of a measurement of the inelastic gamma ray related phenomena while optimizing a duty cycle for a pulsed neutron source used to perform the irradiating.
- [c32] The method as defined in claim 23 wherein a length of time for the detecting long duration neutron burst related phenomena is selected to optimize an accuracy of a long duration burst phenomena related measurement of a property of the formation.
- [c33] The method as defined in claim 23 further comprising monitoring an output of a neutron source used to perform the irradiating, and normalizing measurements of at least one of inelastic gamma ray phenomena, neutron slowing down time and capture cross section made from the detecting thereof.
- [c34] The method as defined in claim 23 further comprising repeating the irradiating, the detecting inelastic gamma ray phenomena, the detecting neutron slowing down phenomena and the detecting capture cross section phenomena for a selected number of times, and detecting background radiation from the formation for a selected time interval thereafter.
- [c35] An instrument for detecting neutron interaction phenomena in earth formations surrounding a wellbore, comprising:

a source of high energy neutrons, the source adapted to emit selected duration bursts of the high-energy neutrons;

radiation detectors, at least one of the detectors adapted to detect neutron slowing down related phenomena, at least one of the detectors adapted to detect inelastic gamma ray related phenomena, at least one of the detectors adapted to detect long duration neutron burst related phenomena; and

a controller operatively coupled to the source and to the radiation detectors, the controller adapted to cause the neutron source to emit bursts of high energy neutrons having a duration selected to enable detection of the inelastic gamma ray phenomena, the controller adapted to cause detection of the inelastic phenomena during each burst, the controller adapted to cause detection of the capture cross section phenomena after the end of a selected number of the bursts.

[c36] The instrument as defined in claim 35 wherein the controller is adapted to operate the detectors to detect background radiation after a selected number of repetitions of the selected number of bursts and detection of the capture cross section phenomena thereafter.

[c37] The instrument as defined in claim 35 further comprising at least one radiation detector operatively coupled to the controller and adapted to detect neutron slowing down related phenomena, the controller adapted to operate the at least one neutron slowing down related phenomena detector after each of the neutron bursts.

[c38] The instrument as defined in claim 35 further comprising at least one detector adapted to monitor an output of the neutron source to enable normalizing measurements of at least one of the inelastic gamma ray related phenomena, the neutron slowing down time related phenomena and the capture cross section related phenomena.

[c39] The instrument as defined in claim 35 wherein the controller is adapted to operate the detectors for the detecting long duration neutron burst related phenomena for a time selected to optimize a duty cycle for the neutron source.

[c40] The instrument as defined in claim 35 wherein the controller is adapted to operate the detectors for the detecting long duration neutron burst related phenomena for a time selected to optimize a statistical precision of a measurement of neutron capture cross section of the formation while optimizing a duty cycle for the neutron source.

[c41] The instrument as defined in claim 35 wherein the controller is adapted to operate the detectors for the detecting long duration neutron burst related phenomena and to operate the source so that a number of the neutron bursts in a measurement cycle and a detection time are selected to optimize a statistical precision of a measurement of a neutron capture cross section of the formation and a statistical precision of a measurement of the inelastic gamma rays while optimizing a duty cycle of the source.

[c42] The instrument as defined in claim 35 wherein the controller is adapted to operate the detectors for the detecting long duration neutron burst related phenomena for a time selected to optimize an accuracy of a long duration burst related measurement of a property of the formation.

[c43] The instrument as defined in claim 35 wherein the controller is adapted to operate the detectors to detect short capture cross section related phenomena after each of the neutron bursts.

[c44] The instrument as defined in claim 35 wherein the at least one of the detectors adapted to detect long duration neutron burst related phenomena comprises a thermal neutron detector.

[c45] The instrument as defined in claim 35 wherein the at least one of the detectors adapted to detect long duration neutron burst related phenomena comprises a gamma ray detector.

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